Nuclear Theory Overview

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Introduction

The main thrust of the research carried out in the Nuclear Theory Group is the physics of nuclear matter under extreme conditions, from production of super-heavy elements in nuclear fusion reactions to effect of the quark-hadron phase transition in neutron stars and to the formation of quark-gluon plasma in ultra-relativistic heavy-ion collisions. While maintaining efforts in the first two directions of research, the main emphasis of the research by the majority of the group has been on the physics relevant to ultra-relativistic heavy-ion collisions and formation of quark-gluon plasma. In particular, we have studied a number of possible signatures of the quark-gluon plasma, from hard QCD processes to soft pion and dilepton production and event-by-event fluctuations.

Recent progress/accomplishments and future plans are described below. During the past year, there were a total of 57 publications, of which 33 were in refereed journals and 12 were in conference proceedings and an additional 12 articles were submitted for publication. A strong visitor program is in place that provides connections to both theoretical and experimental activities in the division.

From quantum field theory to classical transport theory

Our research in relativistic heavy-ion collisions covers a wide variety of topics from formal quantum field theory to phenomenology. One fundamental question relating to the initial conditions formed in heavy-ion collisions is the initial parton distributions inside nuclei that will be liberated through collisions. We used the Wilson renormalization group and effective action formalism to derive an evolution equation for the gluon distribution function at small x that takes into account the effects of multiple Pomeron fusion which reproduces all known perturbative QCD results in the appropriate limits and leads to the unitarization of the gluon distribution function at high energies.
It is then shown numerically (Jalilian-Marian and Wang) that there is a significant reduction in the nuclear gluon distribution function as compared to the naive scaling expectation. This knowledge is crucial in investigation of many experimental processes that will take place at RHIC and LHC such as minijet, heavy quark and direct photon production. The spatial dependence of nuclear shadowing and its influence on observables including particle and transverse energy production as well as on the production of rare processes such as J/ψ and Drell-Yan production are also studied.

We have also investigated the connections between quantum field theoretic and classical description of many body systems. It has been pointed out in finite temperature field theory that one could get the seemingly quantum results of Hard Thermal Loops from an effective action motivated by the Wong equations of motion which describe a classical colored particle interacting with a color field. We showed that starting from the one loop effective action for QCD, one can derive the classical equations of motion which describe the dynamics of classical colored particles

This may help us go beyond the Hard Thermal Loop approximation of finite temperature QCD that will be very useful in calculating physical quantities of interest in a quark-gluon plasma formed in relativistic heavy ion collisions.

Hard Probes of Hot and Dense Matter

Since quark-gluon plasma is expected to form in the early stage of heavy-ion collisions, the most promising probes of QGP is by the means of hard probes that are produced early together with the QGP. There are a few hard probes that have been studied in our group, e.g., high p_T jet and hadron production, J/ψ production and suppression, direct photon and Drell-Yan production.

We continue to work on both the theoretical and phenomenological problem of parton energy loss in dense medium. We started to study multiple parton scattering and induced radiation in the framework of high-twist expansion and factorization. The problem can then condensed into a modified QCD evolution equation which depends on high-twist multiple parton distribution in the medium that the parton is propagating through. One then hopes to find the difference in parton energy between a confined and deconfined medium. The phenomenological effect of parton energy loss in heavy-ion collisions is also studied via high p_T hadron spectra. Predictions of the modification of the hadron spectra are given in the case of parton energy loss in the medium in addition to the effect of initial multiple scattering already persent in pA collisions. The impact of energy loss on heavy quark production at the LHC has also been investigated and shown to be substantial. Since the open charm spectra at CERN SPS are very steep, it is very likely to be enhanced by final state scattering at large p_T. It is pointed out that such modification (partial thermlaization) should also change the dilepton spectra in a limited acceptance and could provide the explanation of the dimuon enhancement observed by NA50 experiments.

Another line of research is concerned with quarkonium suppression as a probe of dense matter. Using a microscopic transport model J/ψ suppression in pA and nucleus-nucleus collisions is studied. It is found that while equilibration of the J/ψ with the medium was unlikely, enough commoving mesons were produced to give approximate agreement with the NA50 data, including the Pb+Pb data. To shed light on the mystery of observed J/ψ suppression at SPS, the behavior of the nuclear target dependence as a function of momentum fraction x_F in pA collisions is also reviewed. It is found that the data might be described by a combination of effects but not through one single mechanism. These includes intrinsic charm production which can explain observed flavor correlations between the projectile and the final-state charm hadrons and can lead to the asymmetry between leading and nonleading charm hadrons production reactions with Σ^-, π^- and p projectiles. Lepton pair and the charmed meson production are also studied in a pure hadronic LEXUS model. The results can be used to find deviation due to formation of QGP. J/ψ in a pure hadronic gas is also studied and found to be negligible at RHIC , although it might be of importance at LHC.

Hadron Properties in Dense Matter

Following the early evolution, the quark-gluon plasma will hadronize. It is also important to study the properties of that hadronic matter, because the relics should carry the footprints of the QGP. On this front, we have studied the properties of the hadronic matter due to restoration of chiral symmetry and other effects related to the phase transition. We have studied the influence of the baryons on soft dilepton production and found that the influence of the baryonic resonance is negligible at 150 GeV and at about a 10 % level at 40 GeV at SPS. We have also calculated predictions for the low energy (40 GeV) measurement, and find no striking new feature, neither in our old approach based on transport in the hadronic phase nor using URQMD events. At present we are also investigation the origin of the difference of the dilepton yield between hydrodynamical and transport calculations.

We have calculated the momentum dependence of the Kaon optical potential based on a dynamic picture of the Λ (1405) (Koch). We find that the attraction felt by anti-K at rest disappears at rather moderate momenta, ~ 200 MeV, calling into question the interpretation of current subthreshold K^- data from GSI. After implementing the potential as well as the in-medium enhanced cross section of $\pi+\Sigma$ K^- $+N$_ into a transport model we find only moderate changes in the final K^- yield, leaving the GSI data as a puzzle.

Progress has been made towards developing practical means for treating the real-time non-equilibrium quantum-field dynamics relevant to the formation of disoriented chiral condensates in high-energy collisions. Moreover, in order to provide guidance for the analysis of experimental data, the semi-classical version of the linear sigma model has been employed for dynamical simulations of systems evolving self-consistently from hot and longitudinally expanding cylindrical configurations.
The resulting asymptotic many-body state of freely moving pions has been subjected to a variety of instructive event-by-event analyses that may serve to bring out the features characteristic of DCC formation, including enhanced factorial moments of the multiplicity distribution for the soft pions and their azimuthal emission correlations. Time evolution of DCC in linear sigma model including the quantum and thermal corrections is also studied.

Event-by-Event Analysis of Heavy-ion Collisions

Due to the large number of particles produced in heavy-ion collisions at RHIC energy, event-by-event analysis of the experimental data becomes possible and can reveal physics that is otherwise difficult to study. We have shown, that event-by-event fluctuations are directly related to multi-particle inclusive distributions. Specifically, presently measured event-by-event fluctuations, which exhibit a Gaussian shape, can be understood in terms of two-particle correlation functions. Furthermore we have proposed a novel method to extract event-by-event fluctuations, the so-called sub-event method, which allows disentangling true (dynamical) correlations from trivial ones, such as those due to quantum statistics and artificial ones, from experimental insufficiencies. We also proposed fluctuation in the π^+/π^- ratio as a robust signal for the state of matter at the chemical freeze-out. We presented our results for a normal state of matter and at the same time established that any sizable deviation from our result should signal a new state of matter, possibly the long-sought quark-gluon plasma. The research in this subject is ongoing.

Astrophysical Implications

The quark-gluon plasma we are seeking in heavy-ion collisions could also exist in the centers of neutron stars and therefore has astronomical consequences. It is demonstrated (Glendenning and Weber) that the creation of this novel state of matter in isolated rotating neutron stars could be accompanied by a dramatic spinning up of an isolated star, pulsars that are extremely massive or very fast spinning. Experimental searches are underway by many groups.

An important development concerning compact stars is the discovery of periodic oscillation in X-ray intensity from neutron stars that are accreting matter from a low-mass companion, and therefore are in a spin-up stage connecting old canonical pulsars that have been spun down to low frequency by their magnetic dipole radiation and the millisecond pulsars. We are making two contributions in this area.
First, models of the X-ray oscillations purport to provide an upper limit on the mass of the neutron star and a radius-mass constraint. We have derived a model-independent value of radius as a function of mass for neutron stars that depends only on general and well-accepted principles. With this, we have been able to establish that strange star candidates can be ordinary neutron stars.

We are doing the inverse of our earlier work on the effect of phase transitions on the rotational properties of neutron stars. The X-ray emitting neutron stars seem to get stuck in their accretion induced spin-up, at least over a very long time. We have found that a phase change induced by the changing central density can cause saturation in incretion induced spin-up, at a much lower frequency than a pulsar that undergoes no phase change in its interior.

Production of Super-heavy Elements

We have made progress (Swiatecki and Myers) in understanding nuclear fission and the dynamics of fusion reactions leading to super-heavy nuclei. Our standard Thomas-Fermi model of nuclear masses and deformations has been shown to reproduce to within a MeV or so the masses of 120 fission saddle-point masses. This makes the model the currently most accurate theory of macroscopic nuclear properties.

The recent production at LBNL of elements 118 and 116 has led us to the concept of Coulomb shielded and unshielded fusion reactions. If this is confirmed (by experiments planned for early 2000), it will be possible to produce more efficiently many heavy and super-heavy elements by using more nearly symmetric projectile-target combinations. We have also collaborated with experimental groups at the 88" cyclotron studying nuclear fission barriers and searching for superdeformed rotating (Jacobi) configurations.